THE PRODUCTION OF COSMIC ELECTRONS FROM MATTER-ANTIMATTER ANNIHILATIONS

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ABSTRACT

The determination of the relative intensities of cosmic negative electrons and positrons will be decisive in determining their origin. Two basic sources have been previously considered as a source for electrons that have been observed near the orbit of the earth:

(1) Cosmic ray protons colliding with interstellar material in the galaxy which eventually result in positrons and negatrons via the decay process and

(2) Negative electron production as a consequence of supernova explosions. In the collisional process, at least half the electrons are expected to be positively charged. Supernova explosions are expected to produce largely electrons. However, experimental data show an abundance of negative to positive electrons of about 2 to 1 in the energy range below 1 BeV. An available physical process that can produce a significant negatron excess is through the mechanism of antiproton-neutron interactions. Annihilations from rest result in a ratio of $^{e+}/_{e-} \approx 0.5$ and an energy distribution for negative and positive electrons, which averages about 100 meV. The electron energy spectra, negative, positive, and combined, all have the following functional form: $N(E) = \frac{Ae^{-a/\lambda}}{E^{\lambda}}$, where N(E) is the number of electrons per unit energy interval, and E is energy. The terms A, a, and λ are constants, whose values are approximately the same for the negative, positive, and combined electron spectra. An antiproton interaction from rest with interstellar material having an abundance ratio of five protons per neutron will result in a positron fraction, $\frac{e^+}{e^+ + e^-} \approx 47$ per cent and a negative electron fraction, $\frac{e^-}{e^+ + e^-} \approx 53$ per cent. It is suggested that a significant portion of the antiprotons

available for interaction are extremely energetic and come from sources external to our galaxy.

I. INTRODUCTION

The purpose of this paper is to present a mechanism that produces both negative and positive electrons such that the ratio of $\frac{e^+}{e^-} < 1$. This has its basis in recent experimental data, specifically in that portion of the cosmic electron energy spectrum below 1 BeV.

The determination of the relative intensities of cosmic negative electrons and positrons will be decisive in determining their origin (Ginzburg 1961). Two basic sources have been previously considered as a source for electrons that have been observed near the orbit of the earth: (1) Cosmic ray protons colliding with interstellar material in the galaxy which eventually result in positrons and negatrons via the decay process. The proton-proton collision hypothesis first postulated by Hayakawa (1952) involves the interaction of protons with interstellar gas in the galaxy, with the subsequent production of pi-mesons and decay electrons. (2) Negative electron production as a consequence of supernova explosions. This source is expected to produce largely negative electrons.

Detailed measurements of the differential electron spectrum have been performed by many workers in recent years (Webber and Chotkowski 1967; Simnett 1967; Hartman 1967; Hartman, Meyer and Hildebrand, 1965; L'Heureux 1967; Earl 1961; DeShong 1964). In the energy regions covered, above 100 MeV, the charge composition of the primary electron component consists of a large negative excess. The production and equilibrium spectra of secondary electrons resulting from the collisional process have been calculated by Ramaty and Lingenfelter (1966). The results of these calculations show a positron excess in the energy spectrum.

In the collisional process, at least half the secondaries are expected to be positively charged. However, Hartman (1967), Hartman et al. (1965), and DeShong (1964) have observed that negative electrons outnumber positrons by about 2 to 1 in the energy regions considered. Thus, this mechanism alone fails to supply a sufficient number of electrons with the appropriate charge. Further, a single power law cannot describe the differential electron spectrum at all measured energies. If all the electrons were directly accelerated in the source region, then the energy spectrum below 500 MeV is not expected to be as flat as reported in Simnett (1967). A change in slope of the primary spectrum suggests different sources for the electron. The total flux is apparently a mixture of several sources, including both processes discussed earlier, and with unknown relative intensities.

A physical process which is the subject of this paper and which can produce a significant negatron excess is through the mechanism of matter-antimatter interactions, specifically antiproton-neutron annihilations, that subsequently produce electrons, neutrinos, and gamma rays via the decay process, indicated as follows:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\quad \mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

ν_μ = muon neutrino

ν_e = electron neutrino

$\bar{\nu}_e$ = electron antineutrino

$\bar{\nu}_\mu$ = muon antineutrino

II. PREDICTIONS OF THE STATISTICAL MODEL

The average pion multiplicity in the annihilation process, according to the Fermi model using covariant phase space integrals, for an interaction radius of 2.2 fermi's, is 5.11. The phase-space integral for the production of n-pions with total energy W in the center of mass system is

$$\left\{\frac{\Omega}{(2\pi)^3}\right\}^n \quad (2M_\pi)^n \quad F_n(W),$$

where $\left\{\frac{\Omega}{(2\pi)^3}\right\}^n$ is a measure of the probability of finding n-pions in a plane wave momentum eigenstate within the interaction volume. Here Ω is the interaction volume, n equals the number of pions, m_π is the pion rest mass, and $F_n(W)$ is the covariant phase-space integral:

$$F_n(W) = \int \left\{ \prod_{j=1}^{n} \frac{d^3 p_j}{\omega_{\pi j}} \quad \delta^3\left[\sum_{j=1}^{n} \vec{p}_j\right] \delta\left[W - \sum_{j=1}^{n} \omega_{\pi j}\right]\right\} ,$$

where W = total energy in the center of mass, system p_j and $\omega_{\pi j}$ are the momentum and energy of the ith particle. In the Fermi model, the only quantities rigorously conserved are the total linear momentum and energy of the system; the conservation of angular momentum, parity, and other observables that may influence the results of the annihilation process are not included.

In this simple statistical model, the total nucleon-antinucleon rest energy of about 1875 MeV is released into an interaction volume. Then statistical equilibrium among different modes is established and pions of corresponding final states are released according to the probability that all the particles are simultaneously available within the interaction volume.

III. PION MULTIPLICITY DISTRIBUTION

The interaction with deuterium results in either the proton or neutron not surviving the annihilations, that is,

$$\bar{p}d \rightarrow a\pi^- + b\pi^+ + n\pi^\circ + P,$$

$$\bar{p}d \rightarrow c\pi^- + d\pi^+ + m\pi^\circ + N$$

where $a = b + 1$

$c = d$

p = proton

d = deuteron

N = neutron

$\bar{p}$ = antiproton

Here we have ignored strange particle production. The mean number of observed charged pions produced as a result of antiproton deuterium interaction at rest is (Kojoian 1966)

$$(n_{\pi}\pm) = 3.07 \pm 0.08$$

Assuming that the energy distribution for neutral pions is the same as that for charged pions, then the average total multiplicity is (Kojoian 1966)

$$(n_{\pi^\circ}\pm) = 5.11 \pm 0.3$$

This value is consistent with the above calculated value of 5.11 and agrees with results of Horowitz, Miller, Murray, and Tripp (1957). The mean number of observed charged pions resulting from the proton-antiproton annihilation mode from rest is 3.03 ± 0.12 (Kojoian 1966), and in antiproton-neutron annihilation from rest is 3.11 ± 0.12 (Kojoian 1966). The charged-pion multiplicity distribution in the antiproton-deuteron annihilation process at rest is shown in Figure 1 (Kojoian 1966). Events with identified strange particles have not been included in the distribution. Then even-numbered charged-pion prongs indicate that a neutron survived the annihilation process; for the odd-numbered charged-pion prongs, the surviving nucleon was a proton. Assuming a statistical distribution of charges (Pais 1960) and relating it to the five pion mode: Fig. 1

(a) Antiproton-proton annihilations result in

$$1.61\ \pi^{+},\ 1.61\ \pi^{-},\ 1.76\ \pi^{0};$$

(b) The antiproton-neutron case produces

$$1.21\ \pi^{+},\ 2.2\ \pi^{-},\ 1.6\ \pi^{0},$$

on the average.

IV. NEGATRON AND POSITRON FRACTIONS ARISING FROM THE ANNIHILATION PROCESS IN INTERSTELLAR SPACE

Assuming an abundance ratio of about 5:1 of protons to neutrons in interstellar space, it is clear from the above calculations that the annihilation mechanism, when the interactions are from rest, will produce a positron fraction of $\frac{e^+}{e^+ + e^-} \approx 47$ per cent and a negative electron fraction of $\frac{e^-}{e^+ + e^-} \approx 53$ per cent.

V. ELECTRON ENERGY SPECTRA ARISING FROM ANTIPROTON-NEUTRON ANNIHILATIONS FROM REST

The negative, positive and combined electron spectra as shown in Figures 2, 3, and 4 are derived from data presented by Chinowsky and Kojoian (1966) in the form of the observed pion momentum distributions that arose from antiproton-neutron annihilations from rest. The following functional form: Figs 2-4

$$N(E) = \frac{Ae^{-a/E}}{E^{\lambda}} \tag{1}$$

where

$N(E)$ = number of electron per unit energy interval

E = energy

$A = 3.2 \times 10^{-4}$

$a = 0.51$

$\lambda = 6.6$

makes a reasonable fit to Figures 2, 3, and 4. The function $N(E) = A/E^{\lambda}$ with $\lambda = 6.42$ produces a reasonable fit for that portion of the slope that is negative in all three figures. The energy distribution spectra for the 3, 4, 5, and 6 charged pion modes are described by the same functional form as in equation (1). However, the 3 and 5 charged pion modes, which are the product of antiproton-neutron annihilations, can be described by a λ of 4.63 and 4.43, for the negative pions, whereas for the positive pions $\lambda = 2.4$ and 4.3. For the 4 and 6 charged pion modes, which is the product of antiproton-proton annihilations,

λ for the negative pion energy distribution is 3.66 and 4.3 and for the corresponding positive pion spectra is 3.66 and 5.4. The shape of the electron energy spectra presented here depends strongly on the source spectra, that is, the pion energy distribution function. The pion spectra are directly and strongly dependent upon the process of generation, in this case, the matter-antimatter annihilation mechanism.

The energy distribution of electrons resulting from subsequent decay of positive pions produced in antiproton-neutron annihilation from rest yielding three charged pions is expected to average about 100 MeV. Figure 2 shows the negative electron distribution as a function of energy. It is characterized by a peak at about 75 MeV. Figure 3 is the corresponding energy distribution for positrons; it peaks at about 65 MeV. Figure 4 is the combined negative and positive electron distribution as a function of energy and shows a peak at about 70 MeV. These three figures are source spectra only, and no attempt was made to adjust each spectrum to include energy losses, that is, synchrotron emission, inverse Compton or energy gain via stochastic accelerative processes.

VI. ANTIMATTER-TO-MATTER RATIO

An estimate on the amount of antimatter available for interaction can be provided from an analysis of observed energetic gamma rays. The gamma rays which are the decay products of the π°'s produced in matter-antimatter annihilations have an average energy of about 100 MeV.

$\pi^\circ \rightarrow \gamma + \gamma$, π° mean lifetime is about 10^{-16} sec.

Thus the gamma ray production is strongly dependent upon the generation of pi mesons. The detection of hard radiation is still in a rudimentary state. But a knowledge of pion production assumes a knowledge of some parameters such as density and composition of the halo and disk of the galaxy. These are poorly known parameters. Observations of the cosmic ray energy spectrum are made in the vicinity of the earth, the results of which are significantly influenced by locally produced secondary electrons above the measuring apparatus: the locally obtained spectrum is assumed to be the same throughout the disk and halo of the galaxy.

With order-of-magnitude adjustments on some parameters such as average densities in the disk and halo of the galaxy, one can arrive at a value for the mean ratio of antimatter to matter, $\alpha \approx 10^{-3}$, which corresponds to the value referenced by Ginzburg and Syrovatskii (1964). Assuming that the entire measured gamma ray intensity resulted from matter-antimatter annihilation in the disk and halo then the annihilation rate would be about 2×10^{-25} cm^{-3} sec^{-1} (Kraushaar and Clark 1962). For $\alpha \approx 2 \times 10^{-3}$ and annihilation arising from rest, the electron flux to proton flux is about 0.7 per cent in the energy range considered; however, this value is about a factor of 4 less than reported by Earls (1961), and more than an order of magnitude less than that reported by Simnett (1967). In order for the annihilation mechanism to be the dominant contributor to the electron flux at the energies considered, the antimatter flux, assuming the interactions are essentially at rest, should be at least 3 to 4 per cent of the corresponding flux of ordinary nuclei.

VII. MULTIPLE PARTICLE PRODUCTION ARISING FROM NUCLEON-ANTINUCLEON INTERACTIONS AT HIGH ENERGIES

At extremely high interaction energies, the physics of pion production is uncertain. It may be that the peak of the meson energy spectrum is not shifted significantly from that at low energies; thus the extra available energy in the center of mass system is available for opening new channels. To determine the number of electrons eventually produced via the decay process, it is necessary to use the statistical theory of multiple particle production. The multiplicity of charged particles depends upon the total interaction energy of the nucleon-antinucleon pair in the laboratory system. It is proportional to $\gamma^{1/4}$, where $\gamma = \frac{E}{Mc^2}$ and E is the total energy of particle-antiparticle pair in the laboratory system and Mc^2 is the particle rest energy. Retaining the above value of α, that is, $\alpha \approx 2 \times 10^{-3}$, the ratio of antimatter to matter, it is necessary to increase the total laboratory energy of nucleon-antinucleon pair to about 10^{14} eV, if the annihilation mechanism is to contribute about equally with the proton-proton collisional mechanisim to the cosmic electron spectrum.

For the particle-antiparticle interaction mechanism to be the dominant contributor to the cosmic electron spectrum, the total energy in the laboratory system of the interacting particles should be above 10^{15} eV.

For an $\alpha \approx 2 \times 10^{-3}$, in order that the annihilation mechanism be a significant contributor to the cosmic electron spectrum, the annihilation must result from collisions with extremely high total energy in the laboratory system, which would suggest that the antiparticles entering into this interaction have probably escaped from neighboring galaxies.

It has been thought that the proton-proton collisional process solely contributes to the observed data in the electron energy range considered here. However, if the annihilation mechanism as a source produces electrons comparable in intensity to that produced by the proton-proton collisional process, then this implies that there probably is some loss mechanism that diminishes the intensity or shifts the energy spectrum of the electrons or that the experimental data is incorrect.

The described mechanism for the production of negative and positive electrons apparently requires the presence of antimatter. To help determine the contribution to the electron spectrum via the matter-antimatter mechanism, a convincing determination of the charge composition of the electron spectrum in the energy range considered should be made, which means essentially placing detectors outside the earth's atmosphere. Another useful experiment would be the determination of the energy spectrum of energetic gamma rays from the decay of π^0's with detectors having a significantly larger detection efficiency than those used previously.

VIII. REFERENCES

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FIGURE LEGENDS

Fig. 1. Multiplicity distribution of the charged-pion prongs in 2071 antiproton-deuteron annihilations at rest. Events with identified K mesons are not included.

Fig. 2. Energy distribution of negative electrons resulting from subsequent decay of negative pions produced in antiproton-neutron annihilations from rest yielding three charged pions.

Fig. 3. Energy distribution of positrons resulting from subsequent decay of positive pions produced in antiproton-neutron annihilations from rest yielding three charged pions.

Fig. 4. Energy distribution of negative and positive electrons resulting from subsequent decay of negative and positive pions produced in antiproton-neutron annihilations from rest yielding three charged pions.

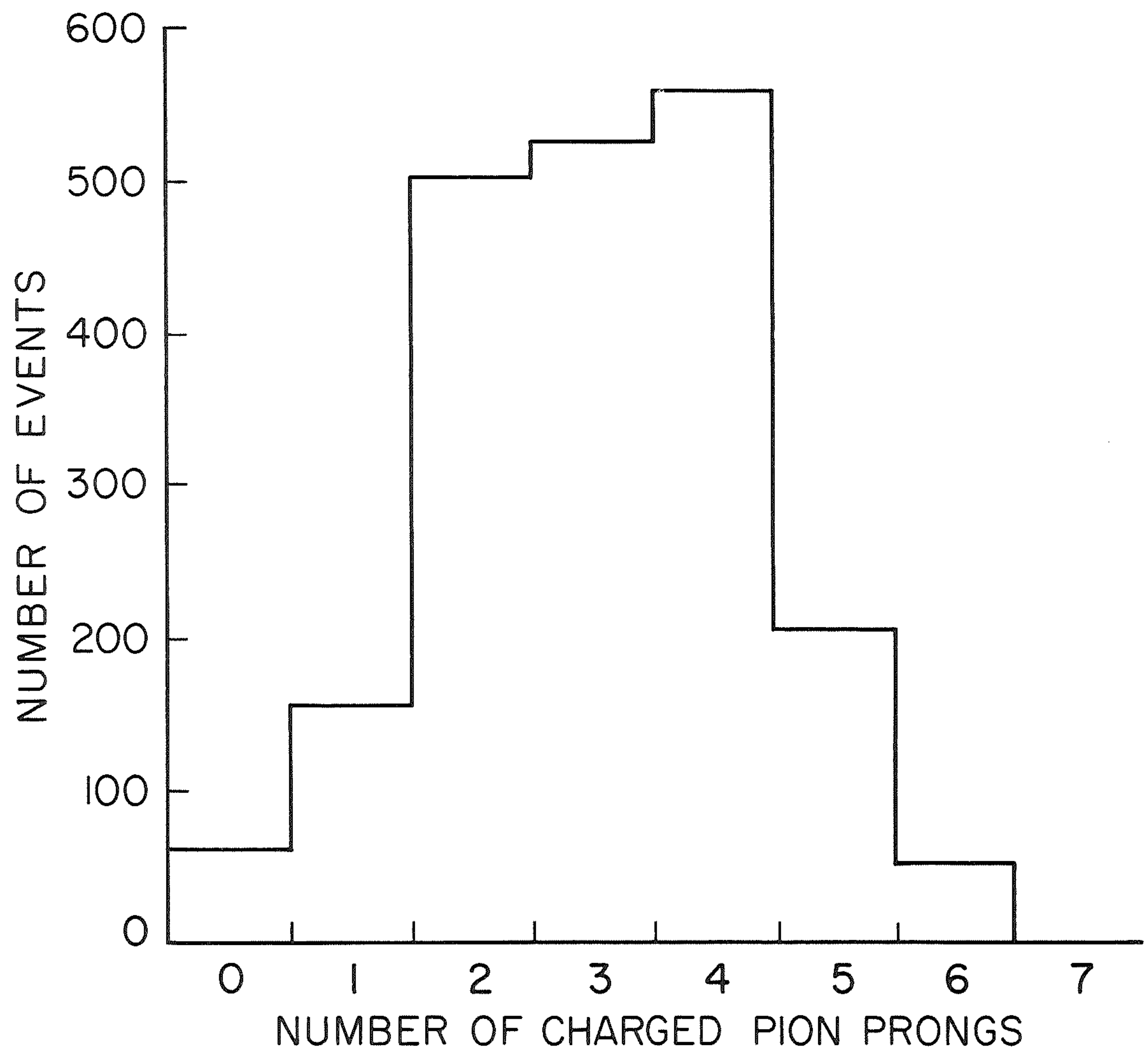

Figure 1.

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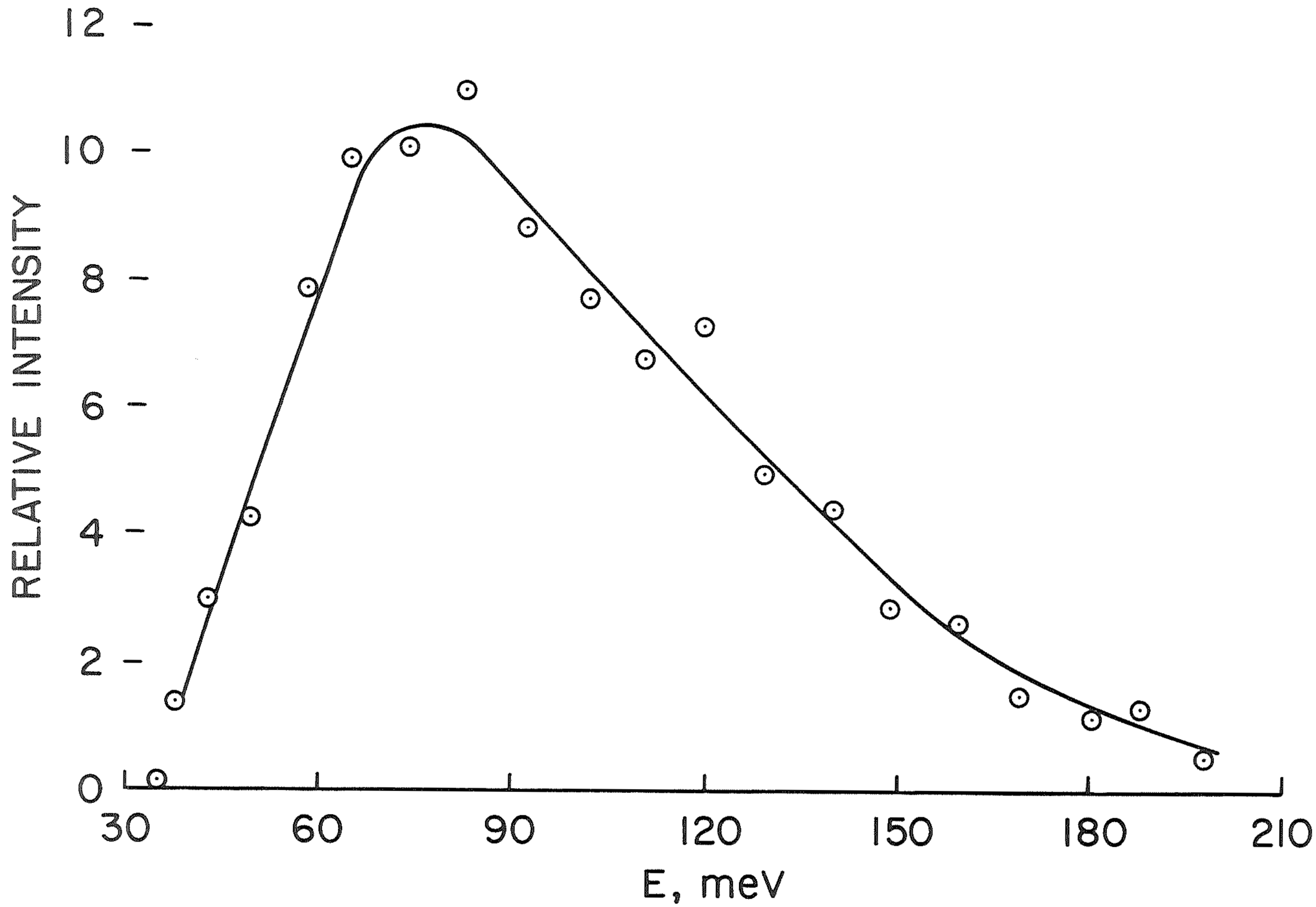

Figure 2.

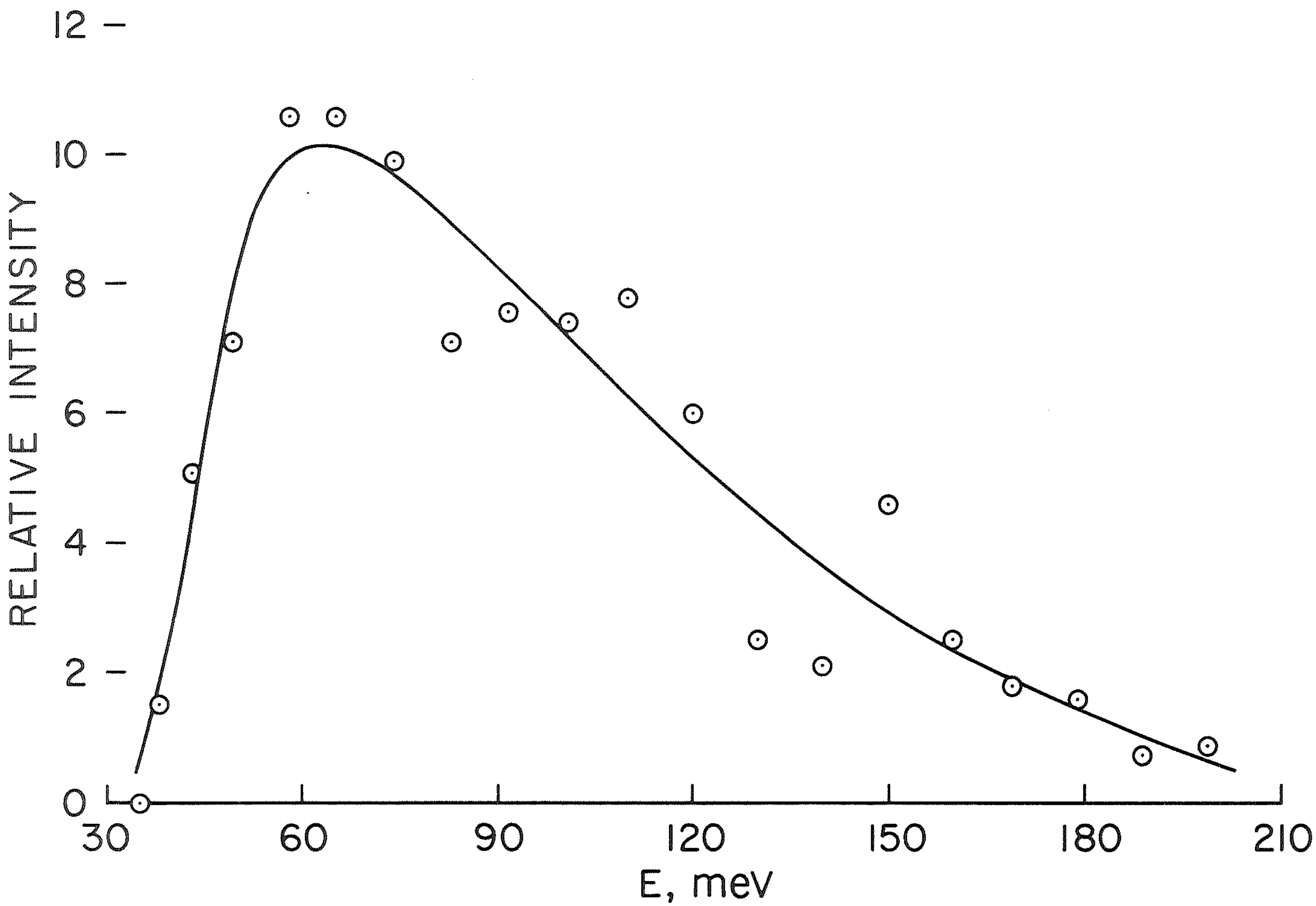

Figure 3.

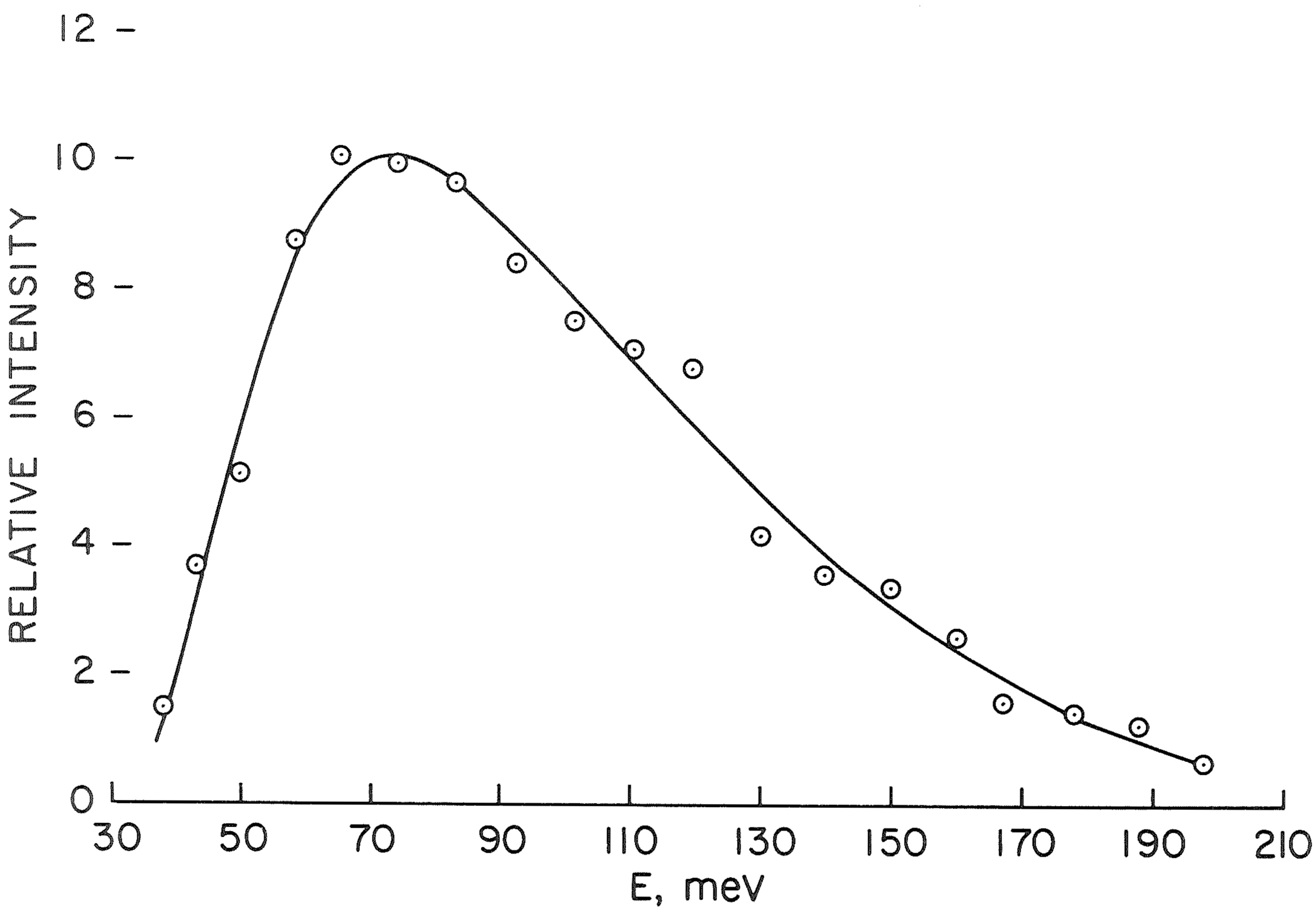

Figure 4.

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